

**SPIN VALVE SENSOR FREE LAYER STRUCTURE  
WITH A COBALT BASED LAYER THAT PROMOTES  
MAGNETIC STABILITY AND HIGH MAGNETORESISTANCE**

**BACKGROUND OF THE INVENTION**

**1. Field of the Invention**

The present invention relates to a spin valve sensor free layer structure with a cobalt based layer that promotes magnetic stability and high magnetoresistance.

**2. Description of the Related Art**

The heart of a computer is an assembly that is referred to as a magnetic disk drive. The magnetic disk drive includes a rotating magnetic disk, a slider that has read and write heads, a suspension arm above the rotating disk and an actuator that swings the suspension arm to place the read and write heads over selected circular tracks on the rotating disk. The suspension arm biases the slider into contact with the surface of the disk when the disk is not rotating but, when the disk rotates, air is swirled by the rotating disk adjacent an air bearing surface (ABS) of the slider causing the slider to ride on an air bearing a slight distance from the surface of the rotating disk. When the slider rides on the air bearing the write and read heads are employed for writing magnetic impressions to and reading magnetic impressions from the rotating disk. The read and write heads are connected to processing circuitry that operates according to a computer program to implement the writing and reading functions.

The write head includes a coil layer embedded in first, second and third insulation layers (insulation stack), the insulation stack being sandwiched between first and second pole piece layers. A gap is formed between the first and second pole piece layers by a nonmagnetic gap layer at an air bearing surface (ABS) of the write head. The pole piece layers are connected at a back gap. Current conducted to the coil layer induces a magnetic field into the pole pieces that fringes across the gap between the pole pieces at the ABS. The fringe field writes information in the form of magnetic impressions in circular tracks on the rotating disk.

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An exemplary high performance read head employs a spin valve sensor for sensing magnetic signal fields from the rotating magnetic disk. The sensor includes a nonmagnetic electrically conductive first spacer layer sandwiched between a ferromagnetic pinned layer and a ferromagnetic free layer. An antiferromagnetic pinning layer interfaces the pinned layer for pinning the magnetic moment of the pinned layer 90° to an air bearing surface (ABS) which is an exposed surface of the sensor that faces the rotating disk. First and second leads are connected to the spin valve sensor for conducting a sense current therethrough. A magnetic moment of the free layer is free to rotate upwardly and downwardly with respect to the ABS from a quiescent or zero bias point position in response to positive and negative magnetic signal fields from the rotating magnetic disk. The quiescent position of the magnetic moment of the free layer, which is preferably parallel to the ABS, is when the sense current is conducted through the sensor without magnetic field signals from the rotating magnetic disk. If the quiescent position of the magnetic moment is not parallel to the ABS the positive and negative responses of the free layer will not be equal which results in read signal asymmetry which is discussed in more detail hereinbelow.

The thickness of the spacer layer is chosen so that shunting of the sense current and a magnetic coupling between the free and pinned layers are minimized. This thickness is typically less than the mean free path of electrons conducted through the sensor. With this arrangement, a portion of the conduction electrons is scattered by the interfaces of the spacer layer with the pinned and free layers. When the magnetic moments of the pinned and free layers are parallel with respect to one another scattering is minimal and when their magnetic moments are antiparallel scattering is maximized. An increase in scattering of conduction electrons increases the resistance of the spin valve sensor and a decrease in scattering of the conduction electrons decreases the resistance of the spin valve sensor. Changes in resistance of the spin valve sensor is a function of  $\cos \theta$ , where  $\theta$  is the angle between the magnetic moments of the pinned and free layers.

The sensitivity of the sensor is quantified as magnetoresistance or magnetoresistive coefficient  $dr/R$  where  $dr$  is the change in resistance of the spin valve sensor from minimum resistance (magnetic moments of free and pinned layers parallel) to maximum resistance (magnetic moments of the free and pinned layers antiparallel) and  $R$  is the resistance of the spin valve sensor at minimum resistance.

A spin valve sensor is sometimes referred to as a giant magnetoresistive (GMR) sensor. The sensitivity of a spin valve sensor depends upon the response of the free layer to signal fields from a rotating magnetic disk. The magnetic moment of the free layer or free layer structure depends upon the material or materials employed for the free layer structure. As the magnetic moment of the free layer structure increases the responsiveness of the free layer structure decreases. This means that for a given field signal from the rotating magnetic disk the magnetic moment of the free layer structure will not rotate as far from its parallel position to the ABS which causes a reduction in signal output.

In order to improve the sensitivity of the spin valve sensor a soft magnetic material, such as nickel iron (NiFe), is employed. It has been found, however, that when the free layer structure employs a cobalt based layer in addition to the nickel iron (NiFe) layer that the magnetoresistive coefficient  $dr/R$  increases when the cobalt based layer is located between and interfaces the nickel iron (NiFe) layer and the copper (Cu) spacer layer. A cobalt based layer, such as cobalt (Co) or cobalt iron (CoFe), has a magnetic moment of approximately 1.7 times the magnetic moment of nickel iron (NiFe) for a given thickness. The addition of a cobalt or cobalt based layer increases the stiffness of the free layer structure in its response to field signals and reduces the sensitivity of the spin valve sensor. Further, the cobalt based material causes the free layer structure to have a hysteresis. This hysteresis is indicated in a hysteresis loop which is a graph of the magnetic moment  $M$  of the free layer structure in response to an applied field  $H$  (signal field) directed perpendicular to the easy axis of the free layer structure. The hysteresis loop, which is referred to as the hard axis loop, has an opening due to the hysteresis which can be on the order of 5 to 7 oersteds. The opening in the hard axis loop is quantified as hard axis coercivity

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$H_c$  which is measured from the origin of the  $x$  and  $y$  axes to the intersection of the loop with the  $x$  axis (applied signal). It has been found that when the hard axis coercivity is high the head generates Barkhausen noise which is due to the fact that the magnetic domains of the cobalt based layer are oriented in different directions.

5 Accordingly, as the signal fields rotate the magnetic moment of the free layer structure some of the magnetic domains do not follow the directions of the signal fields. The magnetic domains that do not readily follow the signal field direction follow behind the signal field direction in an erratic behavior, referred to as jumps in their movements, which causes the aforementioned Barkhausen noise. This  
10 Barkhausen noise is superimposed upon the playback signal which is unacceptable.

In order to keep the hard axis coercivity at an acceptable low level, only very thin cobalt based layers can be employed, such as 2 Å thick. While a 2 Å thick cobalt based layer produces some improvement in the magnetoresistive coefficient  $dr/R$ , it has been found that thicker cobalt based layers will further increase the  
15 magnetoresistive coefficient  $dr/R$ . Considering all factors, including sense current shunting, a cobalt based layer on the order of 15 Å produces the highest magnetoresistive coefficient  $dr/R$ . Unfortunately, a cobalt based layer of this thickness causes the free layer structure to have a hard axis coercivity which unacceptably reduces the sensitivity of the read head to signal fields and produces  
20 Barkhausen noise. Accordingly, it would be desirable if cobalt based layers thicker than 2 Å could be employed in a free layer structure without the aforementioned problems of responsiveness to signal fields and the production of Barkhausen noise.

If the hysteresis or opening in the hard axis loop could be eliminated the aforementioned moment versus applied field graph ( $M/H$  graph) of the responsiveness  
25 of the spin valve sensor would be simply a straight line. This straight line indicates that the read head will be magnetically stable upon the application of the signal fields.

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Another factor affecting the magnetic stability, not involving Barkhausen noise, is the magnetic stability of the pinning layer. A typical pinning layer is nickel oxide (NiO) which pins a magnetic moment of the pinned layer structure. Nickel oxide (NiO) has a blocking temperature of about 220°C wherein the blocking temperature is the temperature at which all of the magnetic spins of the nickel oxide (NiO) pinning layer are free to move in response to an applied field. Unfortunately, there is a blocking temperature distribution wherein some of the magnetic spins of the nickel oxide (NiO) pinning layer are free to move at temperatures below 220°C. The operating temperature in a magnetic disk drive is anywhere between 80°C to 120°C. Should the read head be further heated due to striking an asperity on the rotating magnetic disk or be subjected to an electrostatic discharge (ESD) the temperature of the read head may rise sufficiently so that an unwanted magnetic field may rotate the pinned layer causing some of the magnetic spins of the nickel oxide pinning layer to rotate. When this occurs the nickel oxide (NiO) may not be sufficiently strong (exchange coupling field) to return the magnetic moment of the pinned layer to its original orientation perpendicular to the ABS. This will cause a loss of amplitude and increase asymmetry of the playback signals. Accordingly, it would be desirable if the blocking temperature distribution of the nickel oxide (NiO) and/or an alpha  $\alpha$  iron oxide layer associated therewith could be narrowed so as to improve the magnetic stability of the pinning layer.

In a read head application the hard axis loop or curve of the free layer structure has to be determined after the free layer is subjected to annealing at a high temperature for a period of time. This is due to the fact that during the fabrication of a read/write head combination the aforementioned first, second and third insulation layers are baked photoresist. After spinning a photoresist layer onto a wafer substrate and patterning it, the photoresist layer is annealed at a temperature of approximately 220°C for a period of 6 hours. Accordingly, the hard axis loop or curve for a free layer structure in a read head that is combined with a write head has meaning only after this annealing.

### SUMMARY OF THE INVENTION

I have found that by obliquely ion beam sputtering the cobalt based layer of the free layer structure that the hard axis coercivity can be reduced. I have further found that annealing during the hard back cycle of the insulation layers of the write head further reduces the hard axis coercivity to virtually zero. Ion beam sputtering is accomplished within a chamber which has a substrate where the spin valve sensor is to be fabricated and a target which has the material to be sputtered. An ion beam gun directs ionized gas onto the target which causes the target to sputter atoms of the material toward the substrate. In oblique ion beam sputter deposition the surface planes of the substrate and the target are at an angle with respect to one another. Accordingly, oblique ion beam sputter deposition improves the magnetic stability of a free layer structure having a cobalt based layer which is still further improved by annealing. In an exemplary embodiment the free layer structure may include a nickel iron (NiFe) layer which is sandwiched between first and second cobalt based layers wherein the first cobalt based layer interfaces the copper spacer layer as discussed hereinabove. The second cobalt based layer still further increases the magnetoresistive coefficient  $dr/R$ . It is preferred that all three of these layers be obliquely ion beam sputtered.

I have also employed the oblique ion beam sputter deposition process for improving the magnetic stability of a pinning layer structure that employs a first layer of nickel oxide (NiO) and a second layer of alpha  $\alpha$  iron oxide. While in a preferred embodiment the oblique ion beam sputtering is employed for depositing both of these layers the sputtering may be employed for depositing only one of the layers. The result is that the blocking temperature distribution is decreased so that the pinning layer structure is more stable when the pinned layer is subjected to a field transverse to its pinned direction in the presence of heat.

An object of the present invention is to provide a spin valve sensor for a read head which has improved magnetic stability.

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Another object is to provide a free layer structure with a cobalt or cobalt based layer in a spin valve sensor which promotes an increase in magnetoresistance with virtually no hard axis coercivity.

5 A further object is to provide a highly magnetically stable spin valve sensor that employs one or more cobalt or cobalt based layers in a free layer structure and a pinning layer structure which includes nickel oxide (NiO) and alpha  $\alpha$  iron oxide layers.

10 Still a further object is to provide a spin valve sensor with a pinning layer structure of nickel oxide (NiO) and alpha  $\alpha$  iron oxide that has an improved blocking temperature distribution.

Still another object is to provide various methods of making the aforementioned spin valve sensors.

Other objects and advantages of the invention will become apparent upon reading the following description taken together with the accompanying drawings.

## 15 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a plan view of an exemplary magnetic disk drive;

Fig. 2 is an end view of a slider with a magnetic head of the disk drive as seen in plane 2-2;

20 Fig. 3 is an elevation view of the magnetic disk drive wherein multiple disks and magnetic heads are employed;

Fig. 4 is an isometric illustration of an exemplary suspension system for supporting the slider and magnetic head;

Fig. 5 is an ABS view of the magnetic head taken along plane 5-5 of Fig. 2;

25 Fig. 6 is a partial view of the slider and a piggyback magnetic head as seen in plane 6-6 of Fig. 2;

Fig. 7 is a partial view of the slider and a merged magnetic head as seen in plane 7-7 of Fig. 2;

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Fig. 8 is a partial ABS view of the slider taken along plane 8-8 of Fig. 6 to show the read and write elements of the piggyback magnetic head;

Fig. 9 is a partial ABS view of the slider taken along plane 9-9 of Fig. 7 to show the read and write elements of the merged magnetic head;

5 Fig. 10 is a view taken along plane 10-10 of Figs. 6 or 7 with all material above the coil layer and leads removed;

Fig. 11 is an isometric ABS illustration of a read head which employs an AP pinned spin valve (SV) sensor;

10 Fig. 12 is a schematic illustration of a prior art ion beam sputtering chamber wherein surface planes of the substrate and the target are parallel with respect to one another;

Fig. 13 illustrates an oblique ion beam sputtering chamber which is the same as the sputtering chamber in Fig. 12 except the surface planes of the substrate and the target are at an angle with respect to one another for implementing oblique ion beam deposition on the substrate;

15 Fig. 14 is a schematic illustration of an ion beam gun, target and substrate;

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DI → Fig. 15 is a view taken along plane 15-15 of Fig. 14;

Fig. 16 is an ABS illustration of a first example of a spin valve sensor;

Fig. 17 is an ABS illustration of a second example of a spin valve sensor;

20 Fig. 18 is an ABS illustration of a third example of a spin valve sensor;

Fig. 19 is an ABS illustration of a first example of a free layer structure sandwiched between additional layers;

Fig. 20A shows hard axis and easy axis M/H loops for the structure shown in Fig. 19;

25 Fig. 20B shows hard axis and easy axis M/H loops for the structure in Fig. 19 after annealing;

Fig. 21 is the same as Fig. 19 except oblique ion beam sputter deposition has been employed to construct the free layer structure at a sputtering angle of  $10^\circ$ ;

30 Fig. 22A shows hard axis and easy axis M/H loops for the structure of Fig. 21 before annealing;

Fig. 22B shows a hard axis curve and easy axis M/H loops for the structure of Fig. 21 after annealing;

Fig. 23 is the same as Fig. 21 except oblique ion beam sputter deposition has been employed to form the free layer structure with a sputtering angle of  $20^\circ$ ;

5 Fig. 24A shows hard axis and easy axis M/H loops for the structure in Fig. 23 before annealing;

Fig. 24B shows a hard axis curve and easy axis M/H loops for the structure shown in Fig. 23 after annealing;

10 Fig. 25 is the same as Fig. 23 except the free layer structure has been oblique ion beam sputter deposited at an angle of  $30^\circ$ ;

Fig. 26A shows hard axis and easy axis M/H loops for the structure in Fig. 25 before annealing;

Fig. 26B shows hard axis and easy axis M/H loops for the structure in Fig. 25 after annealing;

15 Fig. 27A shows a cross-section of a cobalt based layer being obliquely ion beam sputtered;

Fig. 27B is the same as Fig. 27A except the cobalt based layer is annealed;

20 Fig. 28 shows a cross-section of a pinning layer structure employing a nickel oxide (NiO) layer and an alpha  $\alpha$  iron oxide layer, wherein the alpha  $\alpha$  iron oxide layer is obliquely ion beam sputter deposited at an angle of  $10^\circ$  to  $30^\circ$ ;

Fig. 29 is the same as Fig. 28 except both layers are obliquely ion beam sputtered at an angle of  $10^\circ$  to  $30^\circ$ .

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

### Magnetic Disk Drive

Referring now to the drawings wherein like reference numerals designate like or similar parts throughout the several views, Figs. 1-3 illustrate a magnetic disk drive 30. The drive 30 includes a spindle 32 that supports and rotates a magnetic disk 34. The spindle 32 is rotated by a spindle motor 36 that is controlled by a motor controller 38. A slider 42 has a combined read and write magnetic head 40 and is supported by a suspension 44 and actuator arm 46 that is rotatably positioned by an actuator 47. A plurality of disks, sliders and suspensions may be employed in a large capacity direct access storage device (DASD) as shown in Fig. 3. The suspension 44 and actuator arm 46 are moved by the actuator 47 to position the slider 42 so that the magnetic head 40 is in a transducing relationship with a surface of the magnetic disk 34. When the disk 34 is rotated by the spindle motor 36 the slider is supported on a thin (typically, .05  $\mu\text{m}$ ) cushion of air (air bearing) between the surface of the disk 34 and the air bearing surface (ABS) 48. The magnetic head 40 may then be employed for writing information to multiple circular tracks on the surface of the disk 34, as well as for reading information therefrom. Processing circuitry 50 exchanges signals, representing such information, with the head 40, provides spindle motor drive signals for rotating the magnetic disk 34, and provides control signals to the actuator for moving the slider to various tracks. In Fig. 4 the slider 42 is shown mounted to a suspension 44. The components described hereinabove may be mounted on a frame 54 of a housing, as shown in Fig. 3.

Fig. 5 is an ABS view of the slider 42 and the magnetic head 40. The slider has a center rail 56 that supports the magnetic head 40, and side rails 58 and 60. The rails 56, 58 and 60 extend from a cross rail 62. With respect to rotation of the magnetic disk 34, the cross rail 62 is at a leading edge 64 of the slider and the magnetic head 40 is at a trailing edge 66 of the slider.

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Fig. 6 is a side cross-sectional elevation view of a piggyback magnetic head 40, which includes a write head portion 70 and a read head portion 72, the read head portion employing a spin valve sensor 74 of the present invention. Fig. 8 is an ABS view of Fig. 6. The spin valve sensor 74 is sandwiched between nonmagnetic electrically insulative first and second read gap layers 76 and 78, and the read gap layers are sandwiched between ferromagnetic first and second shield layers 80 and 82. In response to external magnetic fields, the resistance of the spin valve sensor 74 changes. A sense current  $I_s$  conducted through the sensor causes these resistance changes to be manifested as potential changes. These potential changes are then processed as readback signals by the processing circuitry 50 shown in Fig. 3.

The write head portion 70 of the magnetic head 40 includes a coil layer 84 sandwiched between first and second insulation layers 86 and 88. A third insulation layer 90 may be employed for planarizing the head to eliminate ripples in the second insulation layer caused by the coil layer 84. The first, second and third insulation layers are referred to in the art as an "insulation stack". The coil layer 84 and the first, second and third insulation layers 86, 88 and 90 are sandwiched between first and second pole piece layers 92 and 94. The first and second pole piece layers 92 and 94 are magnetically coupled at a back gap 96 and have first and second pole tips 98 and 100 which are separated by a write gap layer 102 at the ABS. An insulation layer 103 is located between the second shield layer 82 and the first pole piece layer 92. Since the second shield layer 82 and the first pole piece layer 92 are separate layers this head is known as a piggyback head. As shown in Figs. 2 and 4, first and second solder connections 104 and 106 connect leads from the spin valve sensor 74 to leads 112 and 114 on the suspension 44, and third and fourth solder connections 116 and 118 connect leads 120 and 122 from the coil 84 (see Fig. 8) to leads 124 and 126 on the suspension.

Figs. 7 and 9 are the same as Figs. 6 and 8 except the second shield layer 82 and the first pole piece layer 92 are a common layer. This type of head is known as a merged magnetic head. The insulation layer 103 of the piggyback head in Figs. 6 and 8 is omitted.

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Fig. 11 is an isometric ABS illustration of the read head 72 shown in Figs. 6 or 8. The read head 72 includes the present spin valve sensor 130 which is located on an antiferromagnetic (AFM) pinning layer 132. A ferromagnetic pinned layer in the spin valve sensor 130, which is to be described hereinafter, is pinned by the magnetic spins of the pinning layer 132. The AFM pinning layer may be 425 Å of nickel oxide (NiO). First and second hard bias and lead layers 134 and 136 are connected to first and second side edges 138 and 140 of the spin valve sensor. This connection is known in the art as a contiguous junction and is fully described in commonly assigned U. S. Patent 5,018,037 which is incorporated by reference herein. The first hard bias and lead layers 134 include a first hard bias layer 140 and a first lead layer 142 and the second hard bias and lead layers 136 include a second hard bias layer 144 and a second lead layer 146. The hard bias layers 140 and 144 cause magnetic fields to extend longitudinally through the spin valve sensor 130 for stabilizing the magnetic domains therein. The AFM pinning layer 132, the spin valve sensor 130 and the first and second hard bias and lead layers 134 and 136 are located between nonmagnetic electrically insulative first and second read gap layers 148 and 150. The first and second read gap layers 148 and 150 are, in turn, located between ferromagnetic first and second shield layers 152 and 154.

An exemplary prior art sputtering system 200 which may be employed for forming layers of a read head is shown in Fig. 12. The sputtering system 200 includes a chamber 202 which has a valve controlled outlet 204 and a valve controlled inlet 206. The outlet 204 is for the purpose of drawing a vacuum in the chamber and the inlet 206 is for the purpose of introducing an inert gas, such as Argon (Ar), into the chamber. Mounted within the chamber is a substrate 208 which supports a wafer 210 upon which layers of the read head are formed. Opposite the wafer and substrate is a target 212 composed of the material to be sputter deposited on the wafer 210. An ion beam gun 214 is mounted at one end of the chamber 202 for the purpose of directing a beam of ions onto the target 212. Within the ion beam gun high energy electrons collide with atoms, such as argon (Ar) or xenon (Xe) atoms, knocking out one of the electrons of each atom causing atoms to be ionized with a positive charge. Electrons

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knocked out of the atoms have high energy which knock out additional electrons from other atoms which creates a plasma within the ion beam gun 214. Ionized atoms from the ion beam gun strike the target 212 which causes the material of the target to be sputtered and deposited on the wafer 210. In the sputtering system 200 the nominal planes of the substrate 208 and the target 212 are substantially parallel with respect to one another. When the nominal planes are parallel this results in non-oblique sputtering of atoms onto the substrate.

A sputtering system 250 employed in the present invention is shown in Fig. 13. The sputtering chamber 250 is the same as the sputtering chamber 200 except for the angle of the substrate 208 and the wafer 210. The nominal surface planes of the substrate 208 and the target 212 are oriented at a substrate/target angle  $\alpha$  with respect to one another instead of being parallel with respect to one another as shown in Fig. 12. With this arrangement atoms of the material sputtered from the target 212 are deposited on the wafer 210 at a sputtering angle  $\alpha$  to a normal to the nominal surface plane of the substrate 208. While the substrate/target or sputtering angle  $\alpha$  is shown in the plane of the paper, angle  $\alpha$  can be located at any angle within  $360^\circ$  commencing with the plane of the paper and rotated into and out of the paper back to the plane of the paper which will be described in more detail hereinafter. The chamber pressure can be  $10^{-4}$  torr and the working gas may be argon (Ar), krypton (Kr) or xenon (Xe).

Figs. 14 and 15 are schematic diagrams of an ion beam gun 300, a target 302 of some metal and a substrate 304 to illustrate how a substrate/target angle or sputtering angle may comprise rotating one or both of the target 302 and the substrate 304 about one or both of  $x$  and  $y$  axes within nominal surface planes 306 and 308 respectively by various angles  $\alpha$  and  $\beta$  in order to achieve a non-parallel relationship between the target and the substrate for the purpose of achieving oblique ion beam sputtering of the metal onto the substrate 304 with a reduced density. Either angle  $\alpha$  or  $\beta$  or a combination of the angles results in oblique ion beam sputtering (non-normal flux flow) from the center of the target to the center of the substrate. Either the target 302 or the substrate 304 may be maintained stationary while the other

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is rotated by angles  $\alpha$  and/or  $\beta$  to achieve a non-parallel relationship therebetween as shown in Figs. 14 and 15. As an example, Fig. 14 shows the substrate 304 rotated by an angle  $\alpha$  about the  $x$  axis and Fig. 15 shows the substrate rotated by an angle  $\beta$  about the  $y$  axis. In this example the substrate/target angle or sputtering angle comprises angles  $\alpha$  and  $\beta$ . Alternatively, or in addition, the substrate/target angle or sputtering angle may comprise rotating the target 302 about one or both of the  $x$  and  $y$  axes on its nominal surface plane 306. Figs. 14 and 15 show rows and columns of magnetic heads 310 being formed on the substrate 304 with the novel free layer structures of the present invention. Various layers for the read head are shown in Fig. 11 and various layers for the write head are shown in Figs. 6-10.

Seven examples are set forth hereinbelow for explaining and describing the present invention. The first three examples show various ion beam sputter deposition techniques for the purpose of determining whether oblique ion beam sputter deposition affects the magnetoresistive coefficient  $dr/R$  of the spin valve sensor. The last four examples employ different sputter deposition techniques with  $M/H$  graphs showing the results. In all examples the angle  $\alpha$  was  $40^\circ$ .

### Example 1

A first example of a spin valve sensor 400 is shown in Fig. 16 which includes a nonmagnetic electrically conductive spacer layer 402 located between an antiparallel (AP) pinned layer structure 404 and a free layer structure 406. The AP pinned layer structure 404 includes an antiparallel coupling (APC) layer 408 which is located between first and second antiparallel layers (AP1) and (AP2) wherein the first AP pinned layer includes first and second films 410 and 412 and the second AP pinned layer is a single layer 414. A pinning layer 416 pins a magnetic moment 418 of the first AP pinned layer (AP1) 410 which, in turn, by a strong antiparallel coupling, pins a magnetic moment 420 of the second AP pinned layer (AP2) 414 antiparallel thereto. Magnetic moments 418 and 420 are directed perpendicular to the ABS in a direction either toward or away from the ABS. The free layer structure 406 has a middle layer 422 which is located between first and second outside layers 414 and 426. The free

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11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000

layer structure 406 has a magnetic moment 428 which is directed parallel to the ABS and rotates upwardly or downwardly in response to signal fields from a rotating magnetic disk. When a signal field rotates the magnetic moment 428 upwardly the resistance of the spin valve sensor increases and when the signal field rotates the magnetic moment 428 downwardly the resistance of the spin valve sensor decreases so that when the sense current  $I_s$  430 is conducted through the spin valve sensor potential changes due to the resistance changes are processed by the processing circuitry 50 as playback signals. A cap layer 432 is located on the sensor with an intermediate layer 434 located between the cap layer and the top layer 426 of the free layer structure.

The thicknesses and materials of the layers of the spin valve sensor are 425 Å of nickel oxide (NiO) for the pinning layer 416, 10 Å of nickel iron (NiFe) for the first layer 410, 24 Å of cobalt (Co) for the second layer 412, 8 Å of ruthenium (Ru) for the antiparallel coupling layer 48, 24 Å of cobalt (Co) for the second AP pinned layer 414, 22 Å of copper (Cu) for the spacer layer 402, 5 Å of cobalt (Co) for the bottom free layer 424, 54 Å of nickel iron (NiFe) for the middle layer 422, 5 Å of cobalt (Co) for the top free layer 426, 10 Å of copper (Cu) for the intermediate layer 434 and 50 Å of tantalum for the cap layer 432.

All of the layers of the spin valve sensor 400 were formed by ion beam sputter deposition (IBSD) with sputtering angle  $\alpha = 40^\circ$  and sputtering angle  $\beta = 0^\circ$ . Upon conducting tests on the spin valve sensor 400 it was found that the magnetoresistive coefficient  $dr/R$  of the spin valve sensor was 6.33%, the ferromagnetic coupling field  $H_F$  was -0.42 Oe and the resistance  $R$  was 15.82 ohms/sq. The next two examples were run for the purpose of comparing the magnetoresistive coefficients  $dr/R$  with the magnetoresistive coefficient  $dr/R$  of Example 1.

### Example 2

Example 500, shown in Fig. 17, is the same as Example 400 shown in Fig. 16 except the layers 424, 422 and 426 of the free layer structure 406 were obliquely ion

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beam sputter deposited at a sputtering angle  $\alpha = 40^\circ$  and a sputtering angle  $\beta = 20^\circ$  while the remainder of the layers were ion beam sputter deposited at a sputtering angle  $\alpha = 40^\circ$  and sputtering angle  $\beta = 0^\circ$  of  $90^\circ$ . After conducting tests the magnetoresistive coefficient  $dr/R$  was 6.56%, the ferromagnetic coupling field  $H_F$  was 3.54 Oe and the resistance  $R$  was 15.70 ohms/sq. It can be seen from this example that the free layer structure resulted in a slight increase in magnetoresistive coefficient  $dr/R$  as compared to Example 1. The ferromagnetic coupling field increased to 3.54 Oe which is an acceptable level. The resistance  $R$  remained substantially the same. The ferromagnetic coupling field is the field exerted on the free layer structure 406 by the magnetic moment 420 of the second pinned layer. When the ferromagnetic coupling field  $H_F$  is negative it will be antiparallel to the magnetic moment 420 and when it is positive it will be parallel to the magnetic moment 420.

### Example 3

Example 600, shown in Fig. 18, is the same as Example 500 shown in Fig. 17 except in addition to the free layer structure 406 being formed by oblique ion beam sputter deposition the spacer layer 402 is also formed by oblique ion beam sputter deposition with the same angles  $\alpha$  and  $\beta$ . Upon conducting tests the magnetoresistive coefficient  $dr/R$  was 6.67%, the ferromagnetic coupling field  $H_F$  was 10.84 Oe and the resistance  $R$  was 15.66 ohms/sq. While the increase in the magnetoresistive coefficient  $dr/R$  was desirable the increase in the ferromagnetic coupling field  $H_F$  to 10.84 Oe is not desirable when the pinned structure is an antiparallel pinned layer structure 406 as shown in the examples. An AP pinned layer structure has a low net demagnetization field and, when combined with the ferromagnetic coupling field  $H_F$  and a net sense current field  $H_i$ , due to the sense current  $I_s$  430, it becomes difficult to properly bias the magnetic moment 428 of the free layer structure in a parallel position to the ABS when the sensor is in a quiescent state. Accordingly, Example 2 is more desirable than Example 3. However, Examples 2 and 3 show that oblique ion beam sputtering of the free layer structure as well as the spacer layer does not adversely affect the magnetoresistive coefficient  $dr/R$ .

#### Example 4

Example 700, shown in Fig. 19, shows an exemplary free layer structure 701 located between a bottom layer 702 and first and second top layers 704 and 706. The free layer structure 700 has a middle layer 708 located between first and second outside layers 710 and 712. The thicknesses and materials of the layers are 31 Å of copper (Cu) for the bottom layer 702, 5 Å of cobalt (Co) for the first outside layer 710, 54 Å of nickel iron (NiFe) for the middle layer 708, 5 Å of cobalt (Co) for the second outside layer 712, 10 Å of copper (Cu) for the first top layer 704 and 50 Å of tantalum (Ta) for the second top layer 706. All of the layers of Example 700 were ion beam sputter deposited with sputtering angles  $\alpha = 40^\circ$  and  $\beta = 0^\circ$ . Fig. 20A shows easy axis and hard axis loops 720 and 722 in a M/H graph of Example 700 before annealing. The openness of the hard axis loop 722 shows considerable hysteresis when Example 700 is subjected to applied fields. Hard axis coercivity  $H_{CH}$ , which quantifies hysteresis, is measured from the origin of the  $x$  and  $y$  axes to the intersection of the hard axis loop with the  $x$  axis. Example 700 was then subjected to annealing at a temperature of  $220^\circ\text{C}$  for a period of 6 hours which simulates hard baking the photoresist layers in the write head to form the first, second and third insulation layers 86, 88 and 90 in Fig. 6. The easy and hard axis loops after annealing are shown at 730 and 732 in Fig. 20B. It can be seen that the annealing reduced the hard axis coercivity  $H_{CH}$  of Example 700, but an openness in the hard axis loop 732 still remained which will cause Barkhausen noise when Example 700 is used in a read head.

#### Example 5

Example 800, shown in Fig. 21, is the same as Example 700, shown in Fig. 19, except the layers 710, 708 and 712 of the free layer structure have been obliquely ion beam sputter deposited at angles  $\alpha = 40^\circ$  and  $\beta = 10^\circ$ . The easy axis and hard axis loops 820 and 822 for the Example 800 before annealing are shown in Fig. 22A. It can be seen that the hard axis loop 822 has an openness which results in hard axis

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coercivity  $H_{CH}$  which will produce Barkhausen noise. The Example 800 was then subjected to the aforementioned annealing at  $220^{\circ}\text{C}$  for a period of 6 hours. The easy axis and the hard axis loops 830 and 832 after annealing is shown in Fig. 22B. It can be seen that there is no openness in the hard axis loop 832 which means that the hard axis coercivity  $H_{CH}$  is substantially zero. Accordingly, Example 800 shows a considerable improvement over Example 700.

### Example 6

Example 900, shown in Fig. 23, is the same as Example 800 shown in Fig. 21 except the layers 710, 708 and 712 of the free layer structure were obliquely ion beam sputtered at angles  $\alpha = 40^{\circ}$  and  $\beta = 20^{\circ}$ . The easy axis and hard axis loops 920 and 922 before annealing are shown in Fig. 24A. It can be seen that there is an openness to the hard axis loop 922 which will cause Barkhausen noise. Fig. 24B shows an easy axis loop 930 and a hard axis loop 932 which is along the hard axis after annealing at  $220^{\circ}\text{C}$  for a period of 6 hours. It can be seen that there is no opening in the hard axis loop 932 which substantially eliminates Barkhausen noise.

### Example 7

Example 1000 in Fig. 25 is the same as the Example 900 in Fig. 24 except the layers 710, 708 and 712 of the free layer structure were obliquely ion beam sputtered at angles  $\alpha = 40^{\circ}$  and  $\beta = 30^{\circ}$ . The easy axis and hard axis loops 1020 and 1022 before annealing are shown in Fig. 26A. It can be seen that there is a slight openness in the hard axis loop 1022. Fig. 26B shows an easy axis loop 1030 and a hard axis loop 1032 after annealing at a temperature of  $220^{\circ}\text{C}$  for a period of 6 hours. It can be seen that there is no openness in the hard axis loop 1032 which means that Barkhausen noise has been eliminated.

From the above examples it can be seen that a sputtering angle  $\beta$  between  $10^{\circ}$  to  $30^{\circ}$  results in an improved free layer structure which employs a nickel iron (NiFe) layer between first and second cobalt (Co) layers. It should be understood that the invention can be practiced with oblique ion beam sputtering angles  $\beta$  other than  $10^{\circ}$  to

30° and still obtain improvements in the performance of the free layer structure. Further, the invention is not limited to employing two cobalt layers but, optionally, may employ cobalt based layers, such as cobalt iron (CoFe), with only one cobalt based layer being employed between the nickel iron (NiFe) layer and a copper (Cu) spacer layer or an additional cobalt based layer between the nickel iron (NiFe) layer and a capping layer.

Figs. 27A and 27B illustrate a broader concept of the present invention wherein a single cobalt based layer, such as cobalt (Co) or cobalt iron (CoFe), is obliquely ion beam sputtered as shown in Fig. 27A at sputtering angles  $\alpha$  and/or  $\beta$  greater than 0 but less than 90°. This layer can be used for other electronic devices such as random access memory (RAM) devices. Optionally, the cobalt based layer 1100 may be annealed at a temperature above 100° C for a period of time as shown in Fig. 27B. As discussed hereinabove the oblique ion beam sputtering shown in Fig. 27A will improve the hard axis coercivity  $H_{CH}$  of the cobalt based layer 100 which is still further improved or eliminated by employing the annealing step shown in Fig. 27B.

Fig. 28 shows a pinning layer structure 1200 which can be substituted for the pinning layer structure 416 in Fig. 16 in the spin valve sensor. The structure 1200 includes first and second layers 1202 and 1204 wherein the first layer 1202 may be 400 Å of nickel oxide (NiO) and the second layer may be 25 Å of alpha iron oxide ( $\alpha$ FeO). In this embodiment the layer 1202 is ion beam sputter deposited by the prior art sputtering system in Fig. 12 and the layer 1204 is obliquely ion beam sputter deposited at sputtering angles  $\alpha$  and/or  $\beta$  greater than 0. It has been found that this process of fabrication results in a pinning layer structure 1200 which has an improved blocking temperature distribution. Fig. 29 is the same as Fig. 28 except both layers 1202 and 1204 have been ion beam sputter deposited at sputtering angles  $\alpha$  and/or  $\beta$  greater than 0. The pinning layer structure in Fig. 27 has a still further improved blocking temperature distribution which will improve the magnetic stability of the spin valve sensor.

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Clearly, other embodiments and modifications of this invention will occur readily to those of ordinary skill in the art in view of these teachings. Therefore, this invention is to be limited only by the following claims, which include all such embodiments and modifications when viewed in conjunction with the above specification and accompanying drawings.

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**I claim:**

1. A method of determining a value of a function of a variable, the method comprising: receiving a value of the variable; and determining the value of the function of the variable based on the received value of the variable.